

Uprising Smart Technology Based Solutions: Food Safety and Traceability in the Cold Supply Chain through Digital Technologies

Manish Rana¹, Rahul Khokale², Mahendra S. Makesar³, Sunny Sall⁴,
Suresh R. Mestry⁵

¹Department of Computer Engineering, St. John College of Engineering & Management (SJCEM), Palghar, India, dr.manish_rana@yahoo.co.in

²G H Rasoni University (GHRU) Saikheda, Maharashtra –India

³Nagpur Institute of Technology (NIT), Nagpur, Maharashtra -India

⁴St. John College of Engineering & Management (SJCEM) Palghar-India

⁵Rajiv Gandhi Institute of Technology (RGIT), Andheri Mumbai-India

This paper explores the difficulties related to cold chain logistics, including issues with centralized data storage, unreliable information, potential for tampering, and accountability challenges. These problems impact food safety management and undermine consumer rights. To address these issues, the paper proposes a decentralized and secure approach using blockchain technology to monitor fresh agricultural products throughout the cold chain. Current traceability systems, which typically rely on relational databases, are inefficient and insecure, requiring substantial maintenance. The complexity of the food supply chain, with its many stakeholders, further complicates efforts to protect consumers. Traditional Internet of Things (IoT) traceability systems have limitations that restrict consumer access to transaction details and product origins. Blockchain technology, known for its transparency and security, offers a promising alternative to improve traceability. However, existing research has not fully explored the potential, challenges, and implementation of blockchain-based food traceability systems. This paper provides a thorough overview of blockchain technology, including its applications in solving traceability issues, and discusses the challenges and advantages of its implementation. The aim is to provide researchers and practitioners with the knowledge necessary to develop and implement blockchain-based food traceability systems, thereby enhancing traceability, consumer trust, and food sustainability.

Keywords: Cold supply chain, Food safety, Traceability of Food, Smart Technology, Blockchain-based Solution, Digital technologies.

1. Introduction

In modern food supply chains, traditional cold chain logistics encounter several challenges, including centralized data storage, unreliable data, potential data integrity issues, and difficulties in determining accountability. These problems undermine consumer protection and compromise food safety management. This study proposes the integration of blockchain technology to address these issues, aiming to transform current practices with a decentralized, secure, and transparent system for tracking fresh agricultural products throughout the supply chain.

Block-chain technology, originally developed for crypto-currencies like Bit-coin, offers a decentralized network where data is recorded across multiple computers. This distributed nature ensures that data remains immutable, transparent, and secure, making it an ideal solution for overcoming the limitations of traditional cold chain logistics. By eliminating the need for a central authority, block-chain reduces data tampering risks and enhances system reliability.

The technology operates on a consensus mechanism, which requires multiple network nodes to agree on the validity of a transaction before it is recorded, thus ensuring data integrity and reducing fraud risks. Additionally, block-chain uses cryptographic methods to secure transactions, further strengthening the system's security. These characteristics make block-chain a robust option for creating a tamper-resistant traceability system for agricultural products within the cold supply chain.

Current food traceability systems often rely on relational databases that, despite their widespread use, have limitations in efficiency and security. The centralized nature of these databases leads to challenges in maintaining data security and integrity and requires significant maintenance. Furthermore, the complexity of the food supply chain, with its many stakeholders, complicates efforts to address consumer rights and quality concerns. The deficiencies of traditional systems highlight the need for a shift towards more effective food traceability methods.

This research aims to explore block-chain technology's potential to address the challenges in cold chain logistics and food traceability. By thoroughly examining block-chain's features and functionalities, the study seeks to identify solutions that can revolutionize traceability systems. The goal is to provide valuable insights and guidance on implementing block-chain technology in food traceability, thereby improving consumer trust, enhancing food safety, and promoting sustainable practices within the cold supply chain. The ultimate aspiration is to advance transparency, security, and consumer focus in the food industry through block-chain-based traceability systems.

2. Literature Review

Supply Chain Management (SCM)

Supply chain management (SCM) is a crucial component of a company's operations. However, shifting competitive dynamics can make it challenging to synchronize supply and demand processes effectively. Businesses and technologies have grappled with optimizing and

enhancing supply chain operations. Advances in digital technologies have led to more efficient, faster, and flexible processes (Chopra & Meindl, 2016; Hansen & Hill, 1989; Lee & Özer, 2007; Ellis, Morris, & Santagate, 2015). Transparency issues in supply chains impact security, traceability, identity documentation, and verification (Helo & Hao, 2019), making it difficult to establish a trust-based environment (Song, Sung, & Park, 2019). As SCM evolves and integrates more digital tools, systems are becoming increasingly connected, smart, responsive, and transparent.

Blockchain technology has been highlighted as a solution that can reduce costs and enhance efficiency in SCM (Helo & Hao, 2019). By leveraging this advanced technology, supply chain entities and stakeholders can be disintermediated, thereby strengthening trust. Assessing blockchain technology's potential across various economic sectors remains a significant research challenge. It is considered a key competitive force in the business environment, influencing the competitiveness of companies (Song, Sung, & Park, 2019). Blockchain is seen as an innovative tool with the potential to transform SCM business models (Helo & Hao, 2019; Petersen, Hackius, & von See, 2017).

Conversely, SCM can also offer valuable applications for blockchain technology. Implementing blockchain in SCM may represent a business model innovation that enhances value creation and delivery among all stakeholders. Blockchain technology is transforming various sectors, becoming a critical element in developing the Digital Supply Chain (Mikkonen, Korpela, Hallikas, & Pynnonen, 2016). A blockchain-based food supply chain aims to refine processes across quality management, governance, product improvement, sales channels, market dynamics, consumer interactions, logistics, distribution, and financial operations.

Blockchain and Traceability in Supply Chain

Supply value chains are crucial business models in today's global economy, enhancing competitiveness and efficiency by optimizing activity distribution. These chains involve a complex network of processes, activities, and subsystems that require continuous improvement to benefit all participants (Erceg & Sekuloska, 2019). The supply chain encompasses numerous commercial and financial transactions involving various entities, shareholders, information, and documents. According to Harrington's research, companies must adopt digitalization strategies and new technologies to stay competitive. Blockchain technology is one such tool, with many respondents acknowledging its importance for advancing and digitalizing supply chains. Consequently, supply chain management (SCM) is emerging as a key area for blockchain application (Saber, Kouhizadeh, Sarkis, & Shen, 2019). Major corporations like IBM and Maersk have initiated joint ventures to explore blockchain's potential in global trade (IBM, 2015).

Although early research on blockchain in SCM was limited (Salviotti, de Rossi, & Abbatemarco, 2018), interest has grown significantly in recent years, with more studies emerging on blockchain implementation in supply chain management (Verma, 2022; Esmaeilian, Sarkis, Lewis, & Behdad, 2020). Despite this, research on blockchain's application in SCM remains sparse (Fathollahi-Fard, Ahmadi, & Al-e-Hashem, 2020; Fathollahi-Fard, Ahmadi, Goodarzi, & Cheikhrouhou, 2020), with some studies addressing risks and financial benefits (Min, 2019; Nowiński & Kozma, 2017; Sikorski, Haughton, & Kraft, 2017;

Ying, Jia, & Du, 2018). Pournader, Shi, Seuring, and Koh (2019) noted an increase in studies about blockchain in SCM.

Research by Korpela, Hallikas, and Dahlberg (2017) on data integration in SCM using blockchain highlighted the technology's potential. Hackius and Petersen (2017) conducted a study with logistics professionals to explore blockchain's potential uses in SCM, creating application clusters based on best practices. However, a comprehensive viewpoint on blockchain use in SCM is still lacking.

Further research by Queiroz, Telles, and Bonilla (2019) examined the application of blockchain in the sales process between a producer and a supermarket. This process involves recording, coding, and saving contracts on a blockchain, reducing reliance on intermediaries, speeding up transactions, cutting costs, and enhancing trust within the network (Al-Saqaf & Seidler, 2017; Yeoh, 2017). Blockchain's transparency and shared data access offer significant improvements in SCM and logistics, potentially transforming how products are produced, marketed, sold, and delivered (Popper & Lohr, 2017).

Despite its potential, blockchain technology's adoption in logistics is often driven by journalists, consultants, and technology providers rather than logistics operators, who may lack sufficient knowledge about the technology. Blockchain's simplicity, compatibility, and potential benefits align with innovation theory, suggesting a structured approach to its implementation (Iansiti & Lakhani, 2017). This framework includes stages such as single use, localization, substitution, and transformation. Blockchain can improve supply chain management by enhancing efficiency and reducing costs through decentralized shipment tracking and document management (Belu, 2019). Various case studies demonstrate blockchain's potential applications in SCM, showcasing its benefits and challenges.

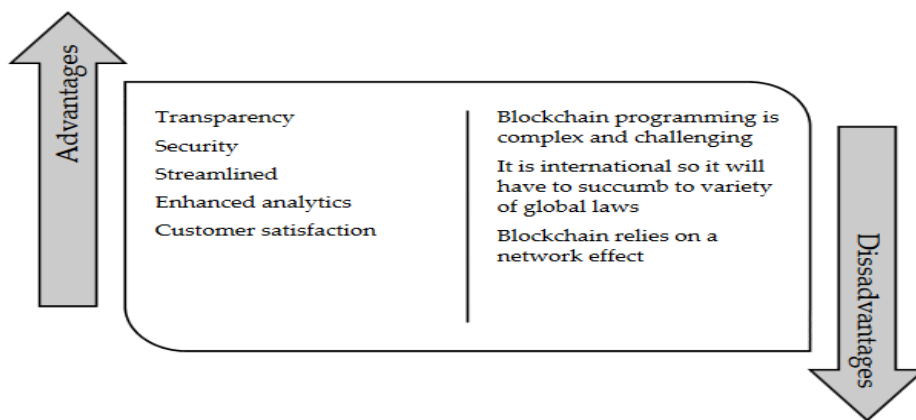


Figure 2.1 Advantages and disadvantages of using blockchain for supply chain.

Table 2.1 Overview of use case exemplars.

Case Exemplars	Description
Ease of paperwork processing	Global container shipping uses a significant amount of paperwork involving costs (money and time). Paper-based documents can be lost, tampered with, and the subject of fraud.
Identify Counterfeit	Counterfeit products present a growing problem for supply chains, and companies must sell the right products to their customers.

Products	
Facilitate Origin Tracking	In food supply chains, outbreaks related to food present challenges, so the companies need to get quick information about where the food came from, which products are impacted, and from which stores they need to be removed.
Operate the Internet of Things	Recently, many logistic objects had sensors used for generating data in the supply chain, and this information needs to be recorded in an unalterable, straightforward way.

Food supply chains offer a prime example of how blockchain technology can enhance transparency and traceability within supply chain management (SCM). While blockchain's adoption for tracking origins provides notable benefits, its implementation across all stages—from production to distribution—varies. In a 2021 survey, supply chain activities held a 10.7% share of the blockchain technology market, underscoring the potential for blockchain to revolutionize SCM. The global blockchain supply chain market, valued at \$93.16 million in 2017, is projected to expand to \$9.85 billion by 2025, with a compound annual growth rate (CAGR) of 80.2%. The growing recognition of blockchain's benefits is driving innovation in supply chain technology, facilitating comprehensive, unified platforms for all participants.

Several notable implementations illustrate blockchain's impact on SCM:

1. IBM and Maersk have developed TradeLens, a blockchain-based solution for efficient information exchange and transaction recording.
2. Kuehne+Nagel launched VGM, a blockchain portal for managing verified gross weight statements.
3. Agility created a blockchain system for tracking and managing container transport.
4. The Transport Alliance, a leading organization in blockchain application for transport, boasts over 60 members and more than 300 blockchain applications.

These examples indicate that successful blockchain integration in SCM hinges on widespread industry adoption (Heutger & Kueckelhaus, 2018). Using blockchain technology in food supply chains demonstrates its ability to enhance origin tracking, transparency, security, and customer satisfaction.

3. Methodology

Research involves a systematic approach to gathering and analyzing data to address specific questions or objectives. This study aims to evaluate the characteristics, benefits, and implementation challenges of blockchain technology in the food industry, particularly for improving food safety and traceability in the cold supply chain. To achieve this, a qualitative research method will be employed.

The study will conduct a systematic literature review to examine various blockchain-based solutions in the food industry, assess their implementation challenges, and identify their potential benefits. This method involves identifying, evaluating, and synthesizing relevant studies to minimize bias and ensure a comprehensive understanding of the topic. A "replicable, scientific, and transparent process" will be adopted to enhance the reliability of the findings.

Two approaches will be used to reduce potential bias: a bibliometric analysis to review existing literature and a content analysis to explore detailed aspects of the reviewed studies. This qualitative research aims to provide insights into how blockchain can improve cold supply chain traceability and food safety.

4. Discussion

Blockchain-Based Traceability

In recent years, there has been a growing demand for traceability information among companies, governments, and consumers due to concerns about food quality and safety. Traceability data can be collected and analyzed through various methods, including business transactions and IoT-enabled devices such as RFID, Wireless Sensor Networks (WSNs), QR codes, and NFC. However, real-time data collection does not necessarily prevent data tampering (Velis et al., 2013; Imeri et al., 2018). Blockchain technology offers a solution by providing mechanisms for ensuring transparency and security, and by facilitating reliable information exchange for traceability management.

Blockchain-based traceability has shown several significant benefits for the agri-food supply chain, including enhanced transparency and accountability (Tama et al., 2017; Kshetri, 2018), fraud prevention and improved traceability (Jin et al., 2017), and enhanced cybersecurity and protection (Galvez et al., 2018; Kshetri, 2018; Banerjee et al., 2018).

In addition to traditional technologies like RFID, IoT, NFC, cloud computing, and big data, blockchain has been proposed as an innovative solution for traceability systems. For instance, a system combining blockchain and NFC for agri-food traceability has been suggested to improve transparency and security (Zhang et al., 2017). Iansiti et al. (2017) also proposed applying blockchain technology to wine traceability, enabling visibility of transactions across the wine supply chain—from grape cultivation to processing, logistics, and consumption. This approach provides secure, transparent, and accurate information sharing. The literature review provides a summary of blockchain solutions addressing traceability challenges, as outlined in

Table 4.1.

Table 4.1 Blockchain solutions for addressing the traceability issues

Traceability issues	How it may be implemented	Feasibility and added value
How to coordinate transaction activities?	Blockchain technology uses digital distributed databases where blocks are linked to each other in an appropriate linear manner and cannot be tampered with.	Propagate data effectively between the participants using blockchain technology
How to verify a transaction is fraudulent or invalid?	The Merkle tree is preserved in the block and used to verify the authenticity of the transaction.	Provide the relevant data to the relevant participants
How to link physical flows to information flows?	Connecting blockchain technology applications with precision agriculture, big data, sensors and IoT platforms, connecting to electronic readable labels (identifiers of physical goods) such as RFID, barcode or 2D grid codes and event recording. The recorded event can be included in a blockchain on this	Keep business confidentiality

	product/supply chain	
How to ensure that only legitimate transactions are recorded in the blockchain?	Participants in the supply chain will add a new block of information at the end of the blockchain only they reach consensus on the transaction.	Information reliability
How to preserve historic records?	When a block is added to the blockchain, it can no longer be tampered and the transaction information is permanently recorded.	Improve the information security

Operational framework of blockchain-based traceability

The study outlines an operational framework for a blockchain-based food traceability system, as illustrated in Figure 4.1. This framework is built on the analysis of existing literature.

Blockchain technology, characterized by its use of cryptographic hashes to link time-stamped blocks, operates in a decentralized and distributed manner. It employs a public consensus mechanism to manage transactions within digital distributed databases (Puthal et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Bozic et al., 2016). Key benefits of using blockchain for traceability include enhanced safety, transparency, traceability, and efficiency. The increasing need for product tracking from farm to store has highlighted blockchain's role in improving the flow of materials and information. Additionally, blockchain, combined with IoT-based devices, is expected to enhance the sustainability and effectiveness of traceability management for agri-food products (Lenes et al., 2017; Galvez et al., 2018).

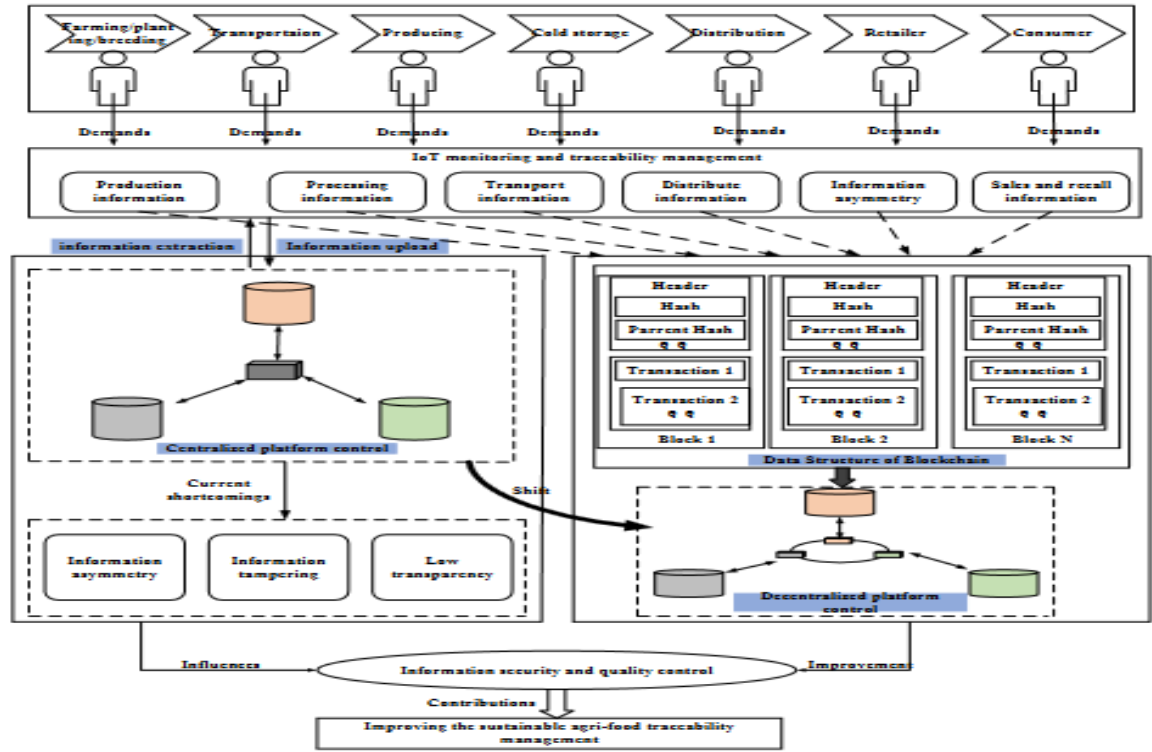


Figure 4.1 The operational framework of blockchain-based traceability

Operational mechanisms of blockchain-based traceability

This section outlines the operational mechanisms of blockchain-based traceability, as illustrated in Figure 4.2. Blockchain technology functions as a digital ledger that is shared, distributed, and resistant to tampering, with data stored in immutable blocks (Kakavand et al., 2017). Each transaction is recorded in a block and linked to others through a series of hash pointers. These blocks are distributed across a peer-to-peer network. Trust among network nodes is established through a consensus mechanism, and each node maintains a replicated copy of the ledger. Transactions are confirmed and verified by consensus among participants. Smart contracts further enhance this system by allowing transactions to be executed automatically without the need for intermediaries (Galvez et al., 2018). This ensures that transactions are secure and cannot be altered.

In the context of agri-food traceability, blockchain can store and verify transaction information in a permanent and unchangeable way. This approach not only eliminates the need for intermediaries, thereby reducing costs and improving efficiency, but also enhances transparency and traceability for consumers (Aiello et al., 2015; Galvez et al., 2018).

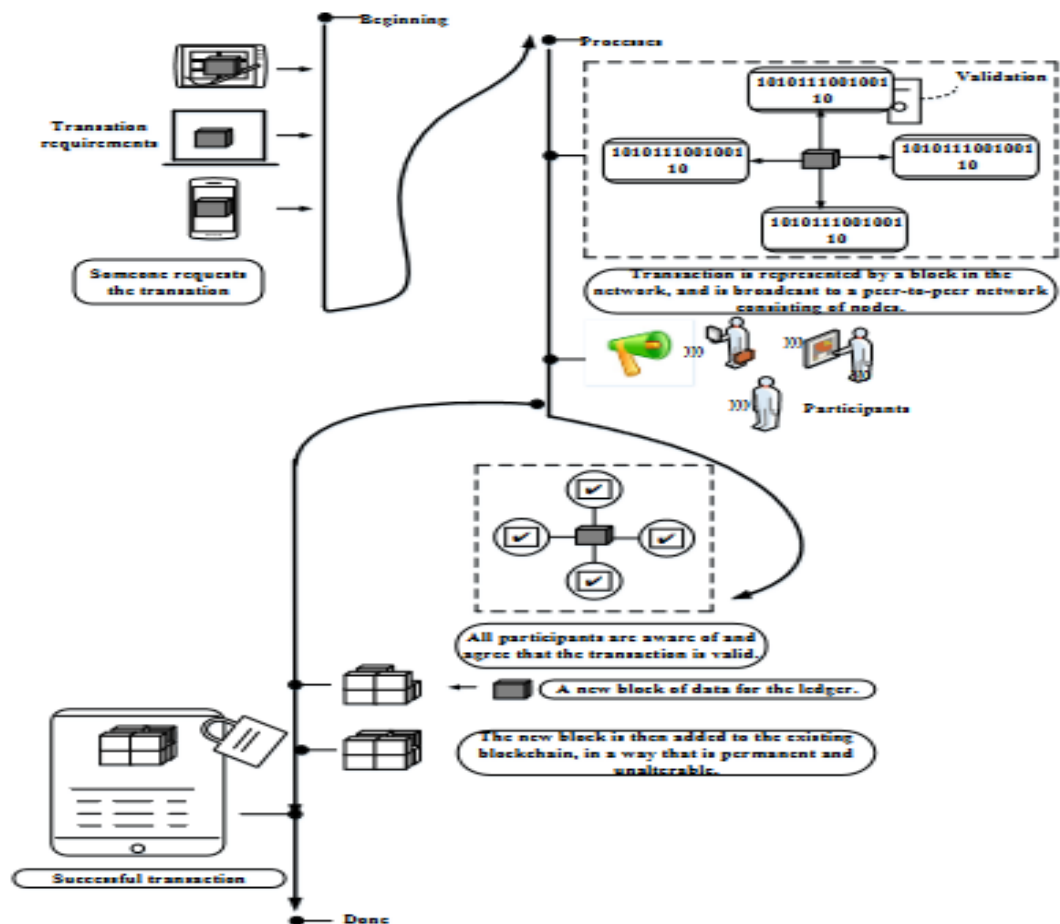


Figure 4.2 Operational mechanism of blockchain technology

Functional characteristics of blockchain-based traceability

Key Features of Blockchain Technology

Blockchain technology is distinguished by several functional characteristics, including:

1. Decentralized and Trustless Network

Blockchain operates through a network of nodes connected in a peer-to-peer system. This decentralized structure ensures that no single point of failure can impact the entire network. Each node independently holds and validates data without relying on a central authority, which enhances system resilience and data integrity (Bahga et al., 2016; Bosona et al., 2013).

2. Smart Contracts in Traceability Processes

Smart contracts automate and enforce transactions within the blockchain. They are programmed to handle specific business rules and processes, thereby facilitating seamless data sharing and process improvement among supply chain participants. When integrated with IoT devices, smart contracts help prevent errors and ensure accurate record-keeping (Andoni et al., 2019; Sikorski et al., 2017).

3. Consensus Mechanism

The consensus mechanism ensures that all participants in the blockchain network agree on the validity of records. This process relies on cryptographic proofs to prevent data tampering and ensure the accuracy of the traceability process (Tian et al., 2017).

4. Transaction Transparency and Anonymity

Blockchain technology provides full transparency for all transactions while allowing participants to remain anonymous. This dual capability enables reliable tracking of agri-food products from harvest to sale, ensuring secure and timely information management (Lnes et al., 2017; Wang et al., 2019).

5. Data Tamper-Proof and Traceable

Transactions recorded in blockchain are immutable and cannot be altered or deleted. This feature allows for thorough querying and tracing of information exchange activities, providing a reliable basis for auditing, operation logging, and logistics tracking (Xu et al., 2019; Dorri et al., 2017).

6. High System and Data Reliability

Blockchain ensures high reliability through distributed data storage across nodes. Each node contributes to maintaining the integrity of the data, and any changes made to the data on one node require validation from more than 51% of the nodes in the network to be accepted (Lin et al., 2017; Galvez et al., 2018).

Development and Evaluation Methods for Blockchain-Based Food Traceability Systems

To effectively develop and assess blockchain-based traceability systems, it is crucial to analyze the requirements of stakeholders in the agri-food supply chain. Quality traceability is a key concern for these stakeholders, and understanding their specific needs is essential for

evaluating blockchain solutions. Table 4.2 provides a summary of the requirements for blockchain-enabled quality traceability, based on a comprehensive literature review.

Table 4.2 Requirements analysis of the blockchain-based traceability system

Req ID	Traceability Requirements	Contribution of blockchain-based traceability system	Requirements type
1	IoT-based data acquisition and transmission	Using blockchain one can control and configure IoT devices	Technical
2	Data security	The whole traceability transaction information and historic actions are recorded and cannot be tampered to achieve data security.	Technical
3	Information transparency	Achieved by consensus mechanisms and data opening of blockchain- based technology.	Technical
4	Data sharing	Blockchain-based traceability enables distributed data sharing.	Technical
5	Transactions speed	Accelerate transactions of blockchain enabled IoT traceability system	Performance
6	Adaptability	Run stably have well scalability	Performance
7	System reliability, stability and scalability	IoT data can remain tamper-proof and distributed in blockchain to improve system reliability and high stability and scalability.	Performance
8	Deployment	Be a system easy to operate.	Performance

Technical and Performance Requirements for Agri-Food Supply Chain Traceability

1. Technical Requirements

To function effectively in a trustless environment, a quality traceability system must ensure that information is secure, reliable, and transparent. Blockchain technology meets these requirements by facilitating distributed data sharing, which enhances trust and security while preventing data tampering.

2. Performance Requirements

As agri-food supply chains expand, the need for increased computing power grows. Nodes are essential for validating transactions and blocks, particularly as IoT devices continuously transmit and share real-time data (Bozic et al., 2016; Fernández-Caramés & Fraga-Lamas, 2018). Key performance indicators for blockchain-based traceability systems include storage capacity, scalability, stability, and processing speed. The system should be energy-efficient, fast, and secure to handle the growing demands of quality traceability.

Architecture Design for Blockchain-Based Food Traceability System

Typically, IoT-based quality traceability systems rely on centralized databases to record information about product quality from production to consumption. Blockchain technology offers a more effective solution for agri-food traceability and anti-counterfeiting due to its tamper-resistant properties (Zhao et al., 2019; Helo et al., 2019). Figure 4.3 illustrates a proposed architecture for a blockchain-based quality traceability system, designed to enhance the transparency and security of transaction information throughout the traceability process. This architecture comprises four layers:

1. Business Layer
2. IoT Layer
3. Blockchain Layer
4. Application Layer

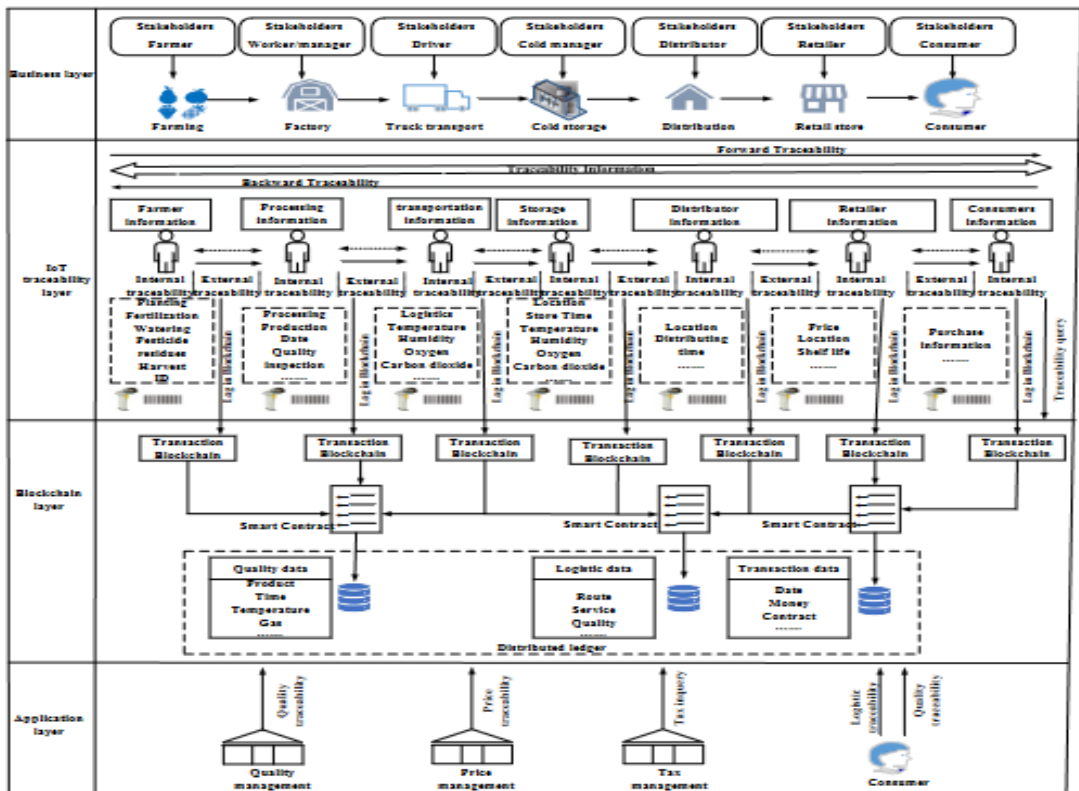


Figure 4.3 Architecture of blockchain-based food traceability system

Business Layer: This layer encompasses all activities in the agri-food supply chain, from farming through to consumption. Each entity within the supply chain manages and controls traceability information. Although digital transformation has not yet fully permeated agri-food transactions and traceability (Bastas et al., 2018), digital ledger technology offers the necessary support for real-time monitoring and management of all processes and transactions in the supply chain.

IoT Traceability Layer: This layer involves collecting traceability data, including quality, processing, logistics, and transaction information, using connected devices such as identity chips, RFID tags, wireless sensor networks (WSNs), and barcode technologies. These devices continuously gather and transmit environmental data, such as temperature, humidity, and gas concentrations. The data collected by these sensors are integrated with blockchain ledgers (Bechini et al., 2008; Imeri et al., 2018).

Blockchain Layer: Blockchain enhances traceability by providing transparency and using *Nanotechnology Perceptions* Vol. 20 No. S8 (2024)

smart contracts to monitor and control quality in real-time. Smart contracts automate logistics planning based on the data collected. They also record a detailed transaction history, tracking the product’s journey from producer through processor, distributor, and retailer to the consumer, thereby ensuring accountability and meeting traceability requirements (Kshetri, 2018; Saberi et al., 2018).

Application Layer: This layer facilitates interaction between traceability chain participants and the information platform. It enables users to access and review the complete flow of logistics, information, and financial transactions.

Suitability and Sustainability Evaluations of Blockchain-Based Traceability Systems

Evaluating the suitability of blockchain-based traceability systems is essential for users and traceability managers. This evaluation helps optimize processes and enhance quality management within the supply chain. Table 4.3 provides detailed performance evaluation criteria based on blockchain information and system resource consumption. Figure 4.4 outlines a flowchart for assessing the suitability and sustainability of blockchain-based traceability systems.

Table 4.3 Performance dimension in achieving the traceability objectives

Performance dimension	Evaluation criteria	Blockchain’s roles
Technical performance	Efficiency of data transmission	Efficiency of data transmission can be increased by digitizing physical process.
	Trusted authority	Blockchain applies to scenarios where there are no trusted permissions or where current trusted permissions may be dispersed.
	Data transparency	Blockchain provides a neutral platform in which all participants can see the published data
	Data integrity	Data integrity is a key historical transaction activity created that can be used to track changes in the ownership and processing of physical assets.
	Data immutability	Data on the blockchain cannot be easily changed.
System performance	System cost (deploying, invoking, and executing smart contracts)	
	Transaction speed	Transaction speed can be increased by DLTs and reducing interactions and communications.
	Dependability	Blockchain can provide a high level of dependability.
	Risk reduction	Solving the holistic sources of risk.
	System stability and scalability	System can run stably and can have well scalability.
	Flexibility and resilience	Higher level of impact with deeper IoT integration in logistics and supply chain.

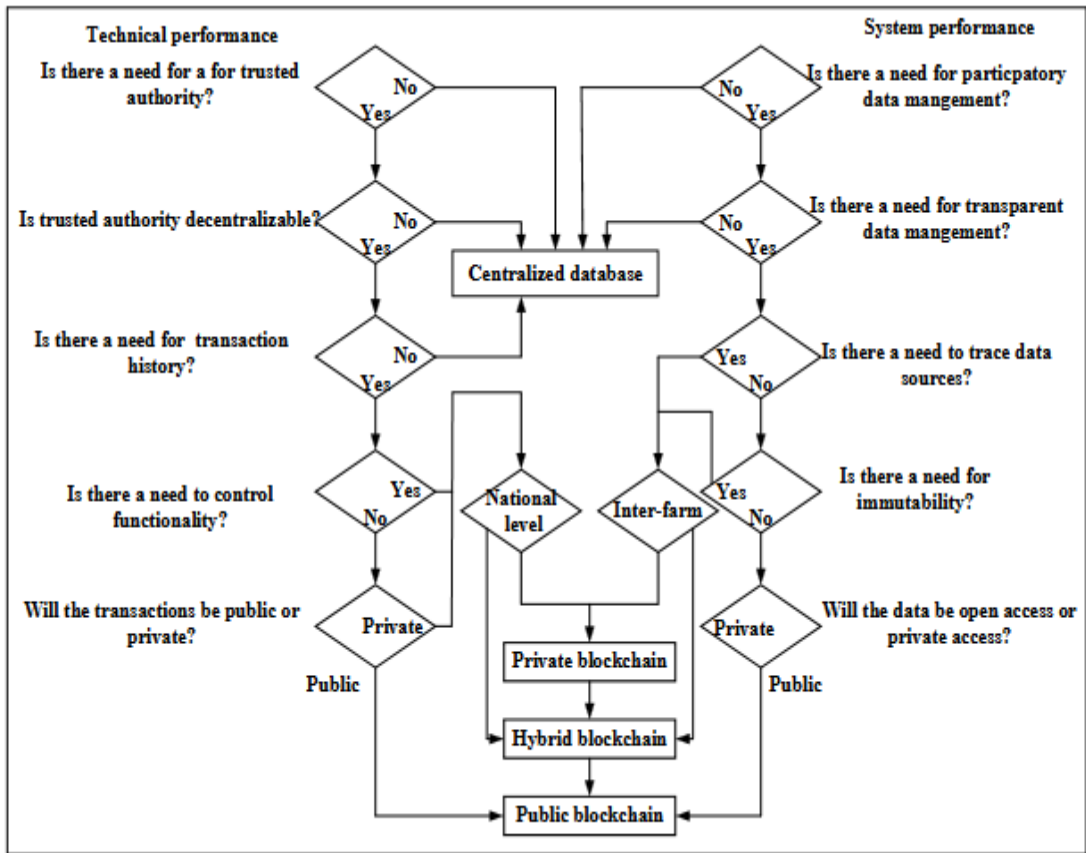


Figure 4.4 A flowchart of suitability and sustainability application analysis for blockchain-based traceability system

Applying Blockchain Technology in Sustainable Food Traceability Management

Blockchain-Based IoT Applications in Traceability Stages:

Stage 1: Farming

Farming is the initial stage in agri-food traceability. IoT smart devices can collect and transmit data related to traceability. This data might include environmental factors like soil quality, water usage, climate conditions, and details about farming practices such as pesticide application and irrigation. Blockchain technology can store this traceability information securely, allowing both farmers and processors to record and verify transactions.

Stage 2: Harvesting

Harvesting time is influenced by seasonal factors. Data related to the harvest, including date, time, and weight measurements, is recorded into the blockchain system. After harvesting, the produce is usually transported in refrigerated trucks to processing facilities for further processing.

Stage 3: Processing

During processing, the focus is on maintaining food safety and quality. Traceability information includes processing conditions, such as equipment used, batch transformations, packaging details, and hygiene methods. This information, including processing tags, is recorded on the blockchain, ensuring that each step is traceable.

Stage 4: Logistics & Cold Storage

This stage involves managing complexity and cost. It is crucial to monitor environmental factors such as temperature and humidity during cold storage. IoT sensors track these conditions and gather data, which is then recorded in the blockchain system. This helps manage logistics more effectively and supports decision-making to minimize spoilage.

Stage 5: Consuming

At the point of sale, blockchain records details such as the product's name, sale date, shelf life, and price. Consumers can access this information to make informed decisions, enhancing transparency and trust in the product's provenance.

5. Conclusions

The digitization of food supply chains through technologies like blockchain can lead to significant improvements in data management and performance. Effective data sharing and analysis across all levels of the supply chain—strategic, tactical, and operational—are crucial for achieving greater efficiency and value. Blockchain technology offers a promising solution to the challenges faced in the cold supply chain, including improving food safety and traceability.

By providing transparency, immutability, and decentralized record-keeping, blockchain can enhance the ability to track and verify food products from farm to table. This technology supports real-time monitoring, accurate tracking, and secure data sharing, which helps mitigate risks, prevent foodborne illnesses, and manage recalls more effectively.

However, adopting blockchain technology comes with challenges, such as scalability, interoperability, and regulatory compliance. For successful implementation, it is essential for stakeholders—including growers, processors, distributors, retailers, and regulators—to collaborate and standardize blockchain solutions. Continued research and innovation are needed to fully realize the potential of blockchain in creating a safe and traceable cold supply chain, ultimately enhancing consumer trust and satisfaction.

6. Recommendations

1. **Enhance Scalability:** Addressing scalability issues is critical for managing high transaction volumes and data storage needs in cold supply chains. Future research should focus on scalability solutions like sharding, sidechains, or layer-two protocols to overcome current limitations of blockchain platforms.

2. Foster Interoperability: Developing standards and protocols to ensure interoperability between different blockchain networks is essential. This will facilitate seamless data exchange and create a unified approach to food safety and traceability across diverse systems.
3. Integrate IoT Devices: Research should explore methods to integrate IoT devices with blockchain technology. This integration will enhance data accuracy and enable proactive monitoring by ensuring secure real-time data transfer, such as temperature and location, while allowing timely responses to anomalies.
4. Prioritize Privacy and Data Protection: Developing privacy-preserving mechanisms and encryption techniques is crucial for maintaining data confidentiality. Future research should focus on balancing traceability and food safety with robust data protection measures.

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